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RESEARCH MEMORANDUM

INJECTION PRINCIPLES FOR LIQUID OXYGEN AND HEPTANE USING TWO-ELEMENT INJECTORS

By Marcus F. Heidmann

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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RESEARCH MEMORANDUM

INJECTION PRINCIPLES FOR LIQUID OXYGEN AND HEPTANE USING TWO-ELEMENT INJECTORS

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SUMMARY

A study of injection principles for liquid oxygen and heptane made previously with single-element injectors was extended for two-element injectors. The mass flow per unit cross-sectional area of the combustor was maintained at the same value as for the single-element study. Eight injectors, produced by two spray orientations of each of the four injection processes, were investigated.

With injection methods that both mixed and atomized the propellants, engine performance changes due to orientation were small. With injection methods that atomized but did not mix the propellants, an orientation conducive to interference of spray patterns of the same propellants caused a substantial decrease in efficiency. Performance also decreased with an injection process that did not effectively mix or atomize propellants. With this process, changes in gas turbulence near the injector were noted.

High-frequency combustion instability, frequently encountered with single elements, did not occur during this two-element study. Design differences related to this change in stability are the use of two elements instead of one centrally located element and the decrease in the length-diameter ratio of the combustion chamber.

INTRODUCTION

This report presents experimental data on the performance of eight different injectors in a heptane-oxygen rocket engine as the continuation of a study in which the relations between propellant preparation and rocket engine performance are systematically sought. In reference 1, ten single-element injectors are evaluated in a 200-pound-thrust rocket engine. Each of these injectors was chosen to exaggerate some part of the injection process such as atomization of fuel only, mixing only, etc. (see ref. 1). The eight injectors evaluated and reported herein represent pairs of four injection elements selected from reference 1; each element was paired in two different orientations. Evaluation of these elements in pairs was intended to reveal any effects of interaction between the single elements. The significance of such interaction in repetitive arrangement of spray patterns is reported in reference 2 and has been noted by other investigators.

An engine rated at a thrust of 400 pounds was used for all injectors. The mass flow per unit cross-sectional area of the combustor was the same as for the single-element study. Mixture ratio was varied by controlling injection pressure; however, all injectors were designed for the same change in pressure drop and total momentum with mixture ratio. 4041

The performance was evaluated from a measure of characteristic exhaust velocity over a mixture-ratio range of about 1.2 to 3.4. Axial velocity of combustion gases as a function of distance from the injector was also determined at one mixture ratio.

The findings of this study were interpreted in terms of the physical processes associated with propellant injection.

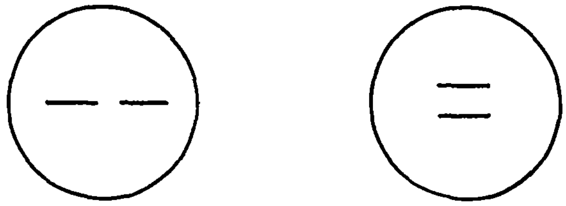
APPARATUS AND PROCEDURE

Rocket Engine

The rocket engine was designed for a nominal thrust level of 400 pounds at a chamber pressure of 300 pounds per square inch. The chamber diameter was 3 inches; the length, 8 inches. A convergent nozzle with a throat diameter of 1.123 inches was used. The engine contraction ratio was 7.1. The injector, uncooled chamber, and uncooled nozzle were separable units. Engine ignition was accomplished with a spark plug in the injector face.

Compared with the 200-pound-thrust investigation of reference 1, the engine length was maintained constant. In this investigation, about twice the chamber area of reference 1 was used, resulting in approximately the same chamber gas velocity with equivalent performance injectors.

Injectors. - Eight injector configurations were investigated. There were two arrangements of each of the four basic injector elements, forming the eight injector configurations. The injection method and principle of the four basic elements were (1) atomization after mixing (impinging-jets injector), (2) atomization before mixing (impinging-sheets injector), (3) atomization without mixing (parallel-sheets injector), and (4) fuel atomization without mixing (fuel-sheet - oxidant-jet injector). The element design was identical to that used in the single-element study of reference 1. These elements were used in pairs with a 1-inch spacing, center to center. The two arrangements produced, respectively, a butt and a parallel orientation of the atomized sheets produced by jet impingement. Diagrammatically, these arrangements are as follows:



Butt Parallel

The injector designs, including water-spray photographs taken at a pressure drop of 100 pounds per square inch, are shown in figure 1. The design pressure drop and total momentum characteristics for the propellant flow from a single element as a function of mixture weight ratio are shown in figure 2.

Performance Measurement

Injector performance was evaluated by determining (1) the characteristic exhaust velocity as a function of the mixture ratio, and (2) the chamber gas velocity as a function of the distance from the injector.

The characteristic exhaust velocity as a function of mixture ratio was obtained from the measurement of chamber pressure and the oxidant- and fuel-flow rates. Chamber pressure was measured at the injector face with both a recording-type Bourdon tube instrument and a strain-gage-type pressure transducer. Flow rates were measured by rotating-vane-type flowmeters. The liquid oxygen was maintained at constant temperature in a liquid-nitrogen bath. Accuracy of calculated exhaust velocity, based on instrumentation errors, was ± 2.5 percent; however, results were generally reproducible to within ± 1 percent.

Combustion-gas velocity as a function of distance from the injector was obtained from streak photographs of the combustion-gas flow. The technique used was similar to that described in reference 1. The photographic arrangement is schematically shown in figure 3. Simultaneous streak photographs of flow as viewed from two directions were obtained. The two directions were displaced 90° about the chamber axis. Transparent plastic chambers were used for these tests. In order to minimize the erosion and burning of plastic, a sheet-metal liner was used within the chamber. Apertures 1/4 inch wide were cut in the liner for the streak photography. Gas velocities were evaluated with an error of approximately ± 20 feet per second. An average variation in gas velocity with distance from the injector was obtained from approximately ten velocity determinations made at each of eight combustor stations.

Test Procedure

The characteristic exhaust velocity was determined for each injector for oxidant-fuel weight ratios (mixture ratio) from about 1.2 to 3.6. Test firings were of about a 3-second duration. For all conditions, the total flow rate was maintained constant at about 1.8 pounds per second.

The axial-gas-velocity variations were evaluated for each injector at a mixture ratio of about 2.4.

RESULTS AND DISCUSSION

Since this investigation is directly related to the study of single-element injectors reported in reference 1, a summary of the single-element performance is presented in table I.

Atomization After Mixing

The characteristic exhaust velocity as a function of mixture ratio for the impinging-jets injector in both butt and parallel orientation is shown in figure 4(a). The performance with butt orientation is slightly lower than with parallel orientation in the fuel-rich region. It does, however, attain a slightly higher peak value.

Comparing the performance of the two-element injectors with that for the single element shows no significant difference in the steady-state performance. With the single element, however, combustion instability with longitudinal pressure oscillations occurred in the mixture-ratio region greater than 2.0 and steady-state combustion could not be obtained in the region. No combustion instability was encountered with the two-element injectors. The comparison is therefore limited to a small mixture-ratio range.

The chamber-gas velocity as determined from streak photographs is shown in figure 4(a). The variation in velocity with distance from the injector is shown for both orientations. Velocity as viewed from two directions is presented. Variations in velocity between these two observations is within measurable accuracy. The agreement indicates that flow is essentially one-dimensional. The exit-velocity level obtained with butt orientation is somewhat higher than with parallel orientation. This trend is in agreement with the higher characteristic-velocity performance obtained with butt orientation. Maximum velocity is also attained in a shorter length with butt orientation; however, the difference may not be significant.

Comparison of the velocity development with that obtained from the single-element study (table I) indicates general agreement. Exact comparison between the single- and two-element studies is impossible, however, because of differences in the experimental tests. In the single-element study, the entire inside surface of the plastic combustion chamber was exposed to combustion gases. The erosion and burning of plastic was considerably greater than in this study, where sheet-metal liners were used.

It may be concluded that single-element performance is representa-
4041 tive of the impinging-jets injector in at least two orientations of two-element injectors. Interference of spray patterns anticipated from a butt orientation may actually have improved maximum experimental performance. In reality, however, small variations between the two orientations for this and succeeding injectors may not be wholly attributed to orientation itself. Small variations in design and machine tolerances may affect performance for reasons not anticipated and not explainable.

Atomization Before Mixing

The characteristic-exhaust-velocity performance for two orientations of the impinging-sheets injector is shown in figure 4(b). Performance is slightly higher for the butt orientation, which has a characteristic exhaust velocity about 125 feet per second higher than the parallel orientation. Comparison of the performance of a single element with that of two elements shows only small differences. The single element exhibited slightly higher performance in the oxidant-rich region and slightly lower in the fuel-rich region.

The gas-velocity variations with chamber length also are shown in figure 4(b). Differences in velocity as viewed from two directions again are small. There again appears to be no significant effect of orientation on the velocity development. These curves differ somewhat in shape from the curve of the single element (table I). In contrast with the continual gas acceleration up to the chamber exit obtained with a single element, the velocity with two elements seems to reach a maximum value before leaving the chamber. Again, exact comparison is impossible because of differences in experimental tests.

In general, the performance of a single-element impinging-sheets injector is indicative of the performance of two adjacent elements in both butt and parallel orientation. The effect of spray-pattern interference anticipated in butt orientation seems beneficial rather than detrimental to performance.

Atomization Without Mixing

The characteristic-exhaust-velocity performance obtained with the parallel-sheets injectors is shown in figure 4(c). Performance with parallel orientations is nearly identical to that of the single element. With butt orientations, however, the performance is appreciably lower. At a mixture ratio of 2.4, the parallel and butt performances are 83 and 58 percent of theoretical, respectively. Combustion instability is not evident during the performance evaluation as is the case with a single element.

Chamber-gas-velocity measurements confirm the result obtained from characteristic exhaust velocity measurements. Figure 4(c) shows that gas velocity attains a higher value with parallel than with butt orientation. In general, the velocity varies linearly with distance from the injector. A similar result was obtained with the single-element study (table I).

These results with the parallel-sheets injector show that single-element performance is not representative of all multielement arrangements. Orientation appreciably influenced the performance. The decrease in characteristic exhaust velocity obtained with butt orientation does not seem related to any fabricating inaccuracies. The same injector body was used for both impinging- and parallel-sheets injectors. The only difference was the design of deflector plates attached to the injector face for the purpose of obtaining oxidant sheets. The deflector plates differed only in the angle of inclination of the impinging surface, as shown in figures 1(d) and (f). For butt orientation, changing the angle of inclination to produce axial oxidant sheets instead of inclined sheets caused the performance to drop significantly.

Preliminary tests with a parallel-sheets injector confirmed its sensitivity to orientation. In these earlier tests, a design was used in which butt and parallel orientation could not be adjusted or maintained with precision. This resulted in erratic performance, as shown in figure 5. Each series of test firings shows a change in performance due to small variations in alinement. Because of other design variations, the performance level in figure 5 is not directly comparable with the single-element performance or with that shown in figure 4(c).

The effect of butt orientation with the parallel-sheets injector may be due to interference of spray patterns. With this injector, the interference is between sprays of like propellants. That is, oxidant sheet interferes with oxidant sheet and fuel sheet interferes with fuel sheet. Such interference would presumably decrease the effectiveness of the atomization and distribution of the propellants. The photographs in figure 1(f) show the effects of this interference on the water sprays. A heavy coalescence of material can be seen in the center of the injection pattern.

Fuel Atomization Without Mixing

The characteristic-exhaust-velocity performance with the fuel-sheet - oxidant-jet injectors is shown in figure 4(d). Compared with the single element, the performance with parallel orientation differs in the oxidant-rich region; at a mixture ratio of 3.0, the characteristic-exhaust-velocity efficiency was 73 percent for a single element and 63 percent for two elements. A similar characteristic occurred with butt orientation; however, in this case, the characteristic-exhaust-velocity efficiencies
4041 differed by only 3 percent at a mixture ratio of 3.0, being 70 percent for two elements. Combustion instability, frequently encountered with the single element, did not occur in the two-element studies.

The gas-velocity development with these injectors is shown in figure 4(d). The variation in velocity with distance from the injector is essentially linear for both orientations. The result is similar to that obtained with a single element. The reaction appears retarded for a short distance near the midpoint of the chamber (4 in. from injector). Also, velocity differences between the two directions of view were largest near the injector. The difference in velocity suggests the presence of large-scale turbulence.

With these fuel-atomizing injectors, changes in performance resulting from the use of two injector elements do not appear related to interference of spray patterns. The only spray-pattern interference anticipated was between fuel sprays in the butt orientation. This interference seemed to cause no appreciable effect on performance. Larger performance changes occurred with parallel orientation for which spray-pattern interference did not exist. The change in performance in this case may be related to the injection process used. With the fuel-atomizing injector, the distribution and vaporization of the oxidant would be expected to control the quantity of propellants that react. The performance therefore would be expected to be more sensitive to chamber turbulence than with an injection process that both mixes and atomizes. The gas velocity indicates the presence of turbulence near the injector. With parallel orientation, therefore, changes in turbulence may have occurred because of interaction between the reaction zones associated with a single element.

Over-all Comparisons

From the foregoing discussion of the various injectors, some generalization can be made on the interference effects between injector elements. It appears that with injector elements designed both to mix and to atomize the propellants, such as the impinging-jets and impinging-sheets injectors, the interference effects are relatively small. Such preparation apparently permits the propellants injected from each element to react independently of propellants from the neighboring element.

The marginal improvement in performance obtained with a butt orientation of sprays may have resulted from an increase in propellant mixing. The interference in this case is between sprays of mixed propellants and, although the interference may have been detrimental to propellant atomization, it could be conducive to better mixing.

For the case of atomization without mixing, such as the parallel-sheets injector, interference between sprays of the same propellant caused an appreciable decrease in performance. The spray interference apparently decreased the effectiveness of the atomization and mixing. With a parallel orientation of these spray patterns, the interference effect seemed to be completely eliminated. This result tends to confirm the sensitivity of performance to changes in propellant atomization reported in reference 1.

When the fuel alone was atomized, small performance changes seemed to be related to changes in chamber turbulence. These changes in performance are probably a characteristic of inadequate propellant preparation. With such injection, chamber turbulence plays a significant part in the over-all combustion process.

Combustion instability was not encountered with any of the two-element injectors. This is in direct contrast to the results with single elements for which some instability was exhibited by all injection methods. Streak photographs of combustion showed that the two-element impinging-jets injectors were marginally stable during starting transients but continuous oscillation did not persist. In the single-element study, it was the impinging-jets injector that showed the most pronounced oscillations. The following differences in configuration may account for the increase in stability: (1) the propellant injection was not centrally located in the injector face as it was for the single element, and (2) the length-to-diameter ratio of the two-element injector was smaller than for the single-element study. Both of these factors may influence acoustical damping within the chamber.

CONCLUDING REMARKS

The results obtained with two-element injectors indicates that interference effects between elements are minimized when propellants injected from each element are adequately mixed and atomized. These results should be further substantiated through studies made with more elements in order to examine the influence of mass-flow distribution, element spacing, and other orientations on interference effects between elements. If independent action of injector elements using practical spacing is confirmed, the knowledge of propellant preparation requirements and combustion processes may be expanded through fundamental studies performed with individual injector elements. This knowledge may then be applied to the design of injectors for engines of all thrust levels.

The results obtained with injector elements apply specifically to liquid oxygen and heptane. The applicability of these results to other propellant combinations has not been determined.

SUMMARY OF RESULTS

Interference effects between adjacent elements in two-element injectors were studied experimentally. The study was made with a nominal 400-pound-thrust engine using liquid oxygen and heptane as propellants. Characteristic-exhaust-velocity and chamber-gas-velocity measurements were made. Eight injectors, produced by two orientations of each of the four injection processes, were investigated. The two orientations were butt and parallel arrangements of sprays.

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The following results were obtained as functions of the injection processes:

1. In tests of atomization with mixing, the two-element performance in both orientations was nearly identical to that of a single element.

2. In tests of atomization without mixing, performance with parallel orientation where no spray interference existed was similar to the single-element performance, whereas performance with an orientation causing butt interference of sprays was about 25 percentage points lower.

3. In tests of fuel atomization without mixing, the engine performance was relatively unaffected with a butt orientation of fuel sprays, but a decrease in performance in the oxidant-rich region occurred with a parallel orientation of sprays.

4. Combustion instability with longitudinal pressure oscillations, frequently encountered during tests with single-element injectors, was not evident during any two-element firings.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 5, 1956

REFERENCES

1. Heidmann, M. F., and Auble, C. M.: Injection Principles from Combustion Studies in a 200-Pound-Thrust Rocket Engine Using Liquid Oxygen and Heptane. NACA RM E55C22, 1955.

2. Datner, P. P., and Dawson, E. E.: Testing of Repetitive-Pattern Injectors in 1000-Lb Thrust Chambers with Chamber-to-Throat Area Ratios of 4.5 Using WFNA and JP-3. Rep. 555, Aerojet Eng. Corp., July 25, 1952. (Contract AF 33(038)-2733, Proj. MX-1079, E.O. No. 539-44.)

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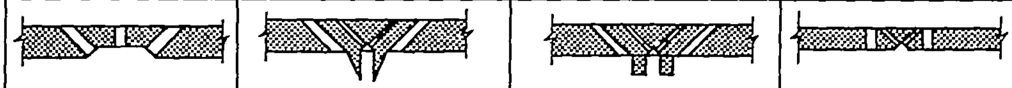
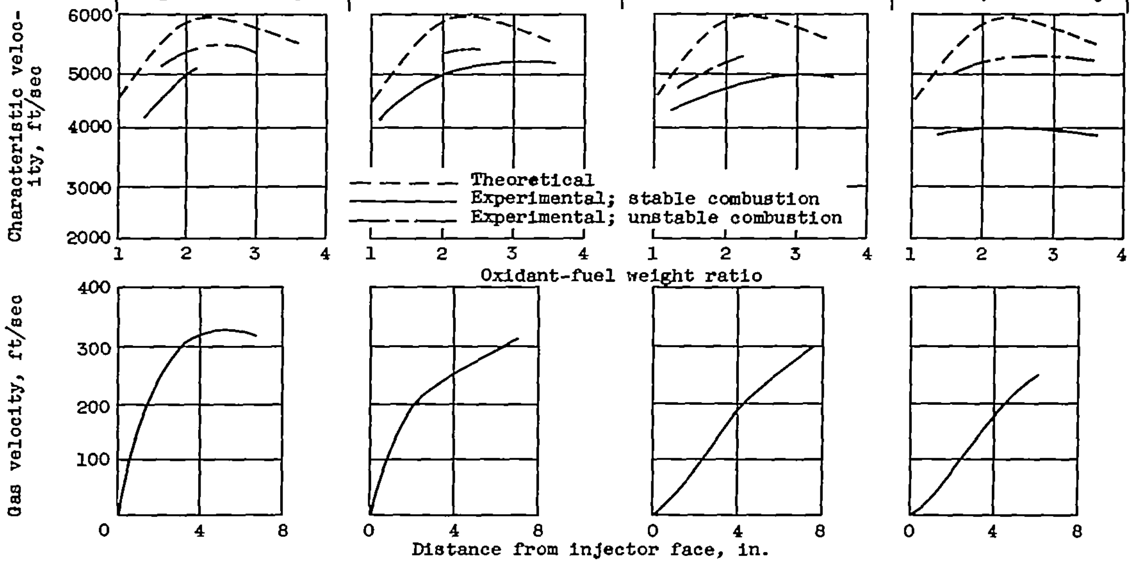
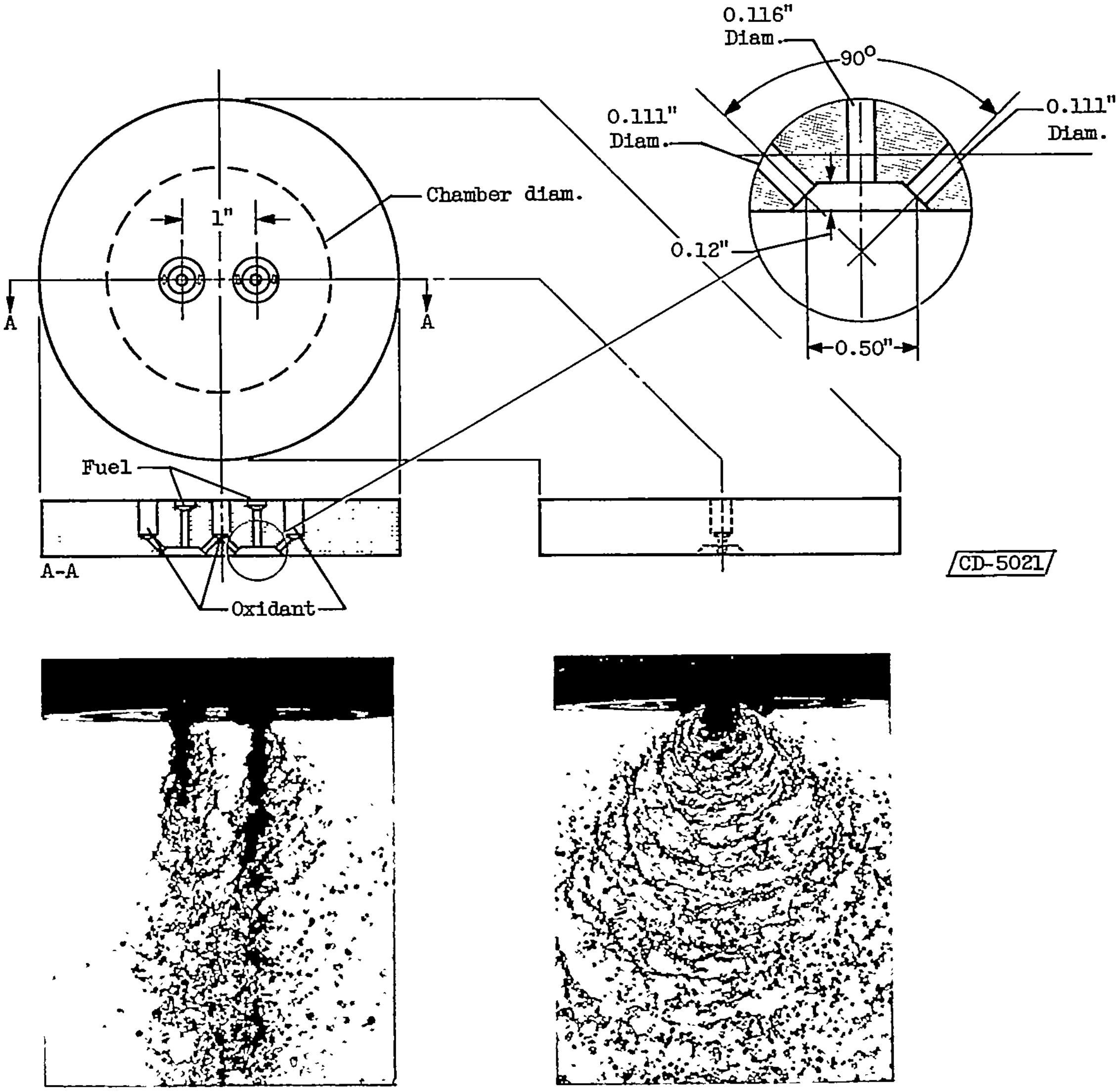
TABLE I. - SUMMARY OF EFFECTS OF PROPELLANT PREPARATION ON COMBUSTION AND PERFORMANCE OF SINGLE-ELEMENT INJECTORS (REF. 1)

Mixing		Atomization without mixing	
Before atomization	After atomization	Oxidant and fuel atomization	Fuel atomization
			
Impinging jet; long stream length	Impinging sheets	Parallel sheets	Parallel fuel sheets; oxidant jet



Combustion and ignition characteristics

Unstable at oxidant-fuel ratios larger than 2.0; longitudinal oscillations with presence of high harmonic and lateral mode; intermittent detonations during ignition with longitudinal and lateral oscillations during transition to full thrust	Inherently stable; one nonreproducible unstable condition encountered; smooth start and transition to full thrust	Generally stable longitudinal oscillations during instability; smooth start and transition to full thrust	Inherently unstable; longitudinal oscillations with presence of high harmonic or lateral mode; intermittent detonations during ignition with longitudinal oscillations during transition to full thrust



(a) Impinging-jets injector; parallel orientation of sprays.

Figure 1. - Injector design and water-spray photographs.

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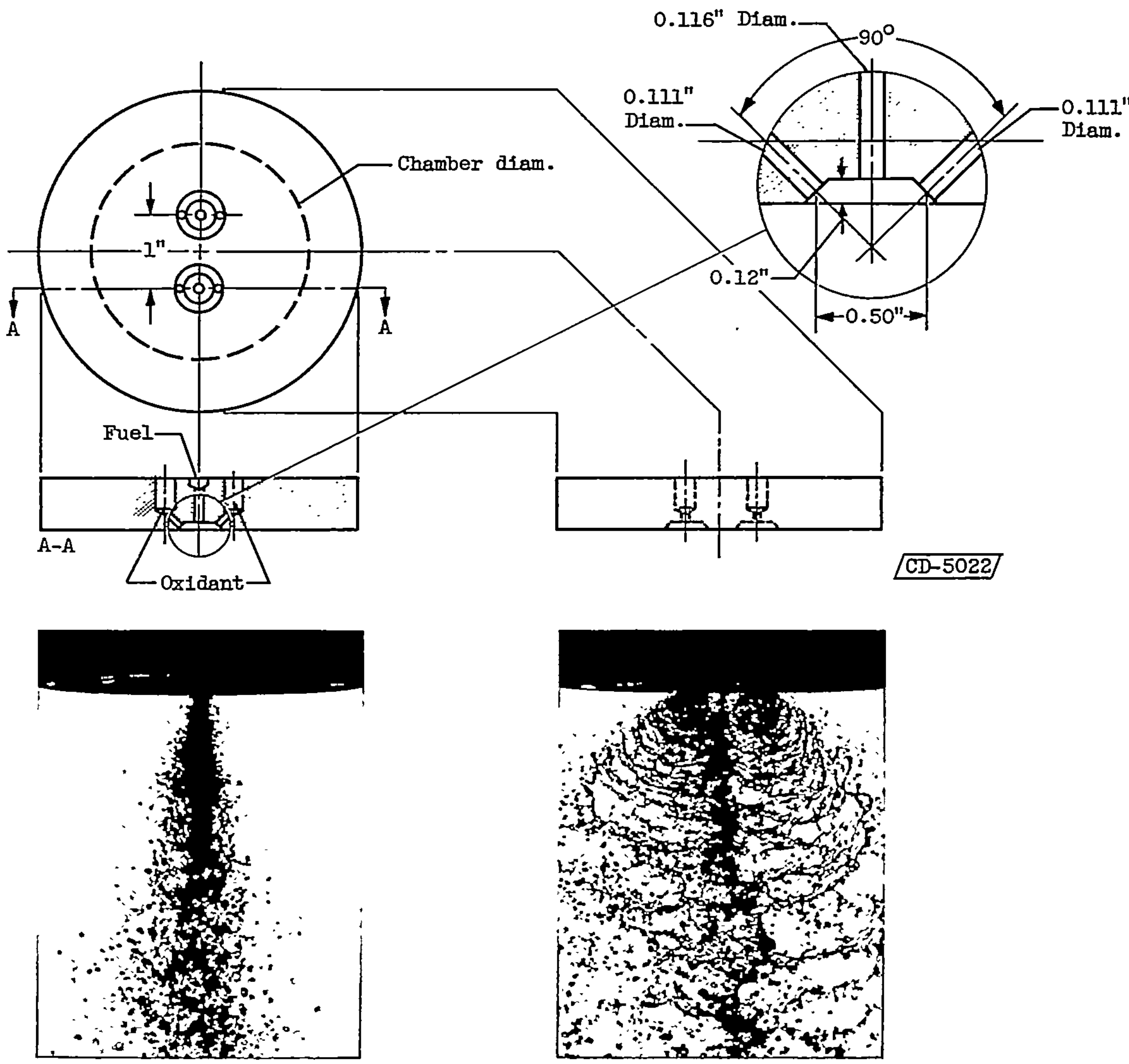

(b) Impinging-jets injector; butt orientation of sprays.

Figure 1. - Continued. Injector design and water-spray photographs.

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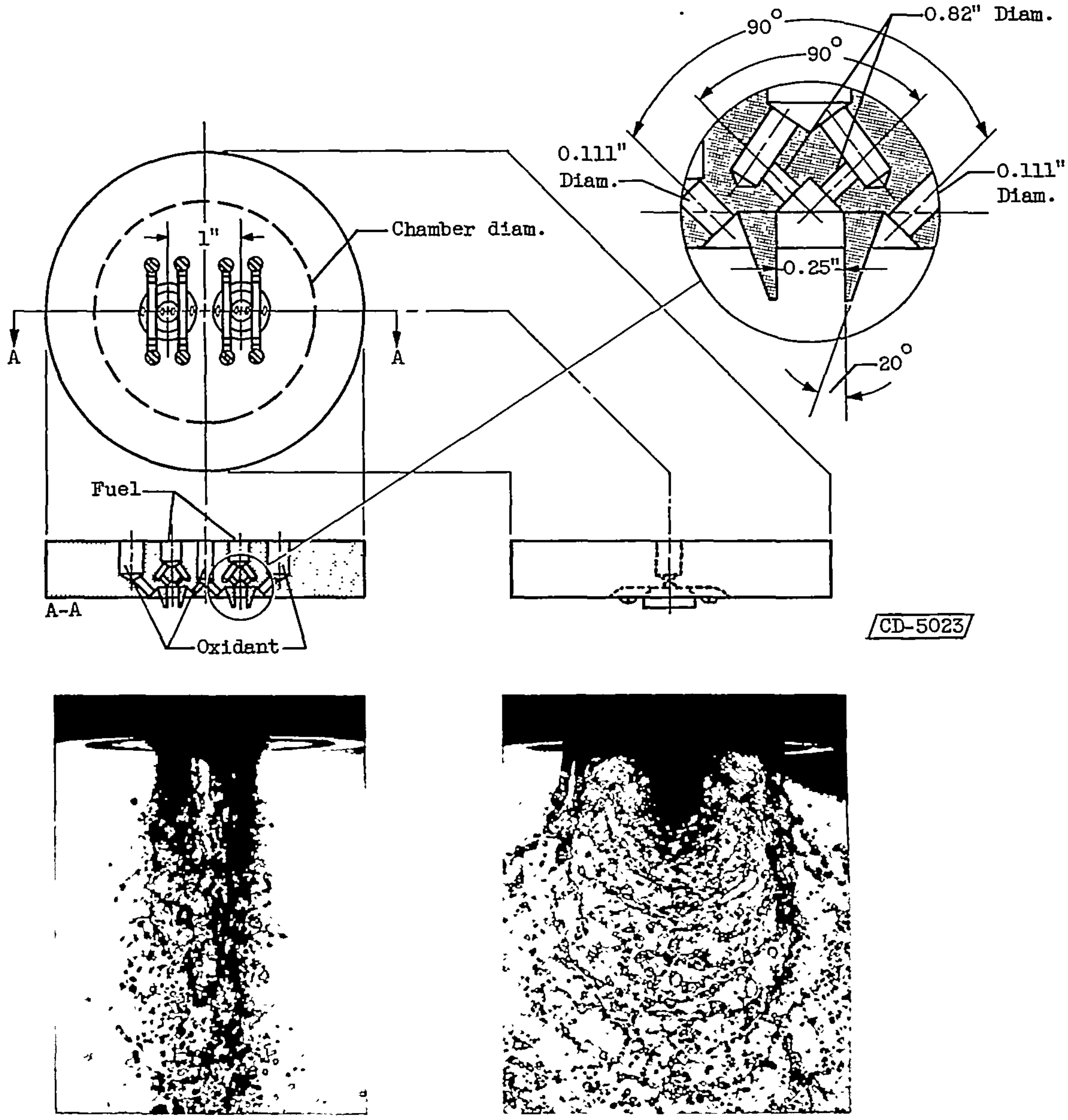

(c) Impinging-sheets injector; parallel orientation of sprays.

Figure 1. - Continued. Injector design and water-spray photographs.

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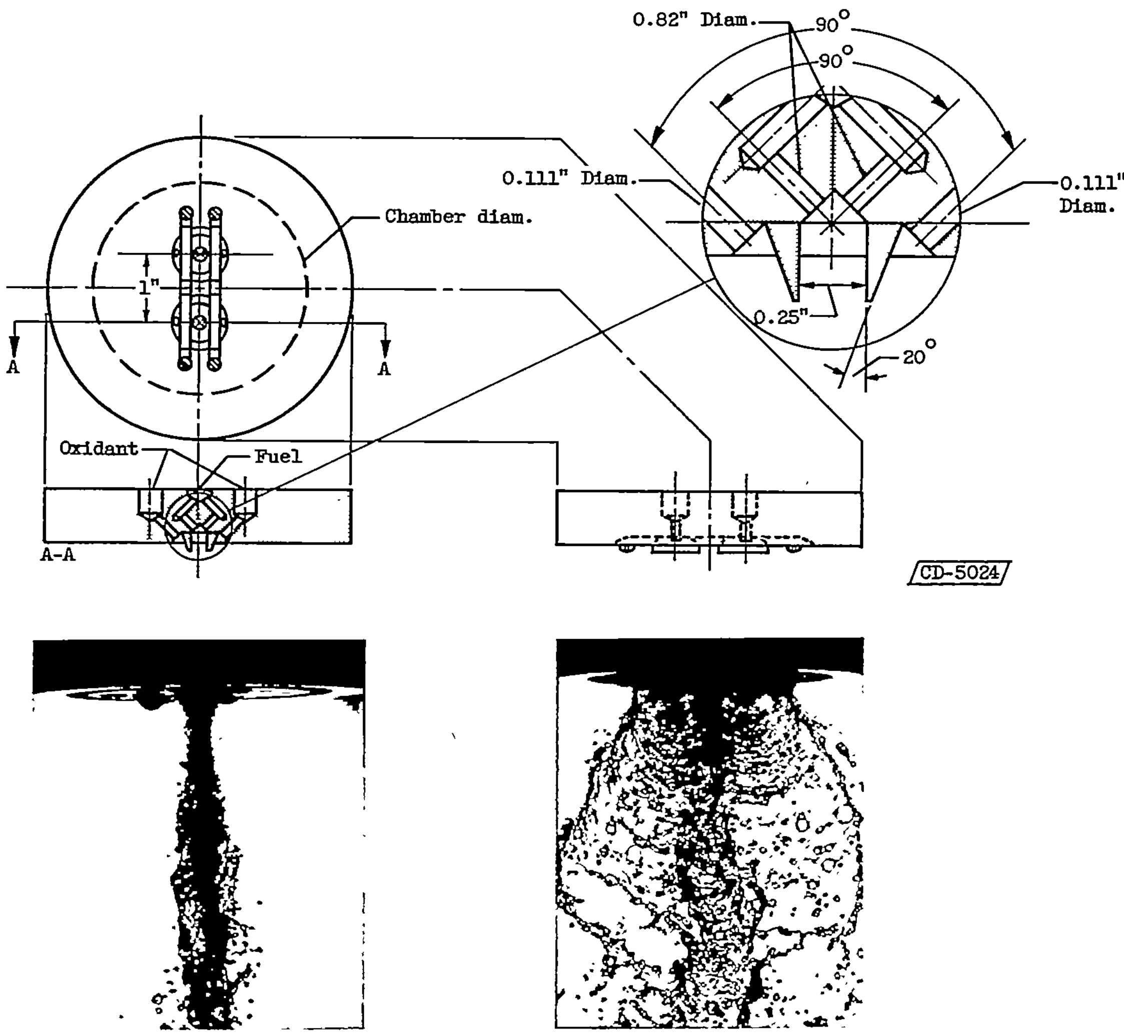
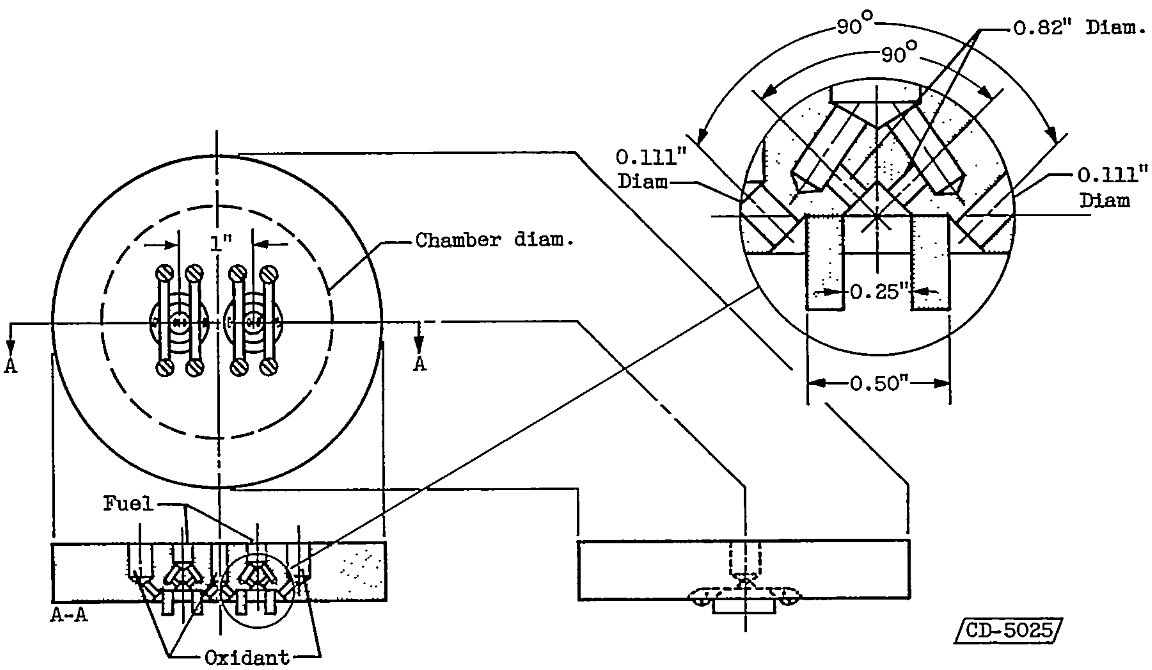
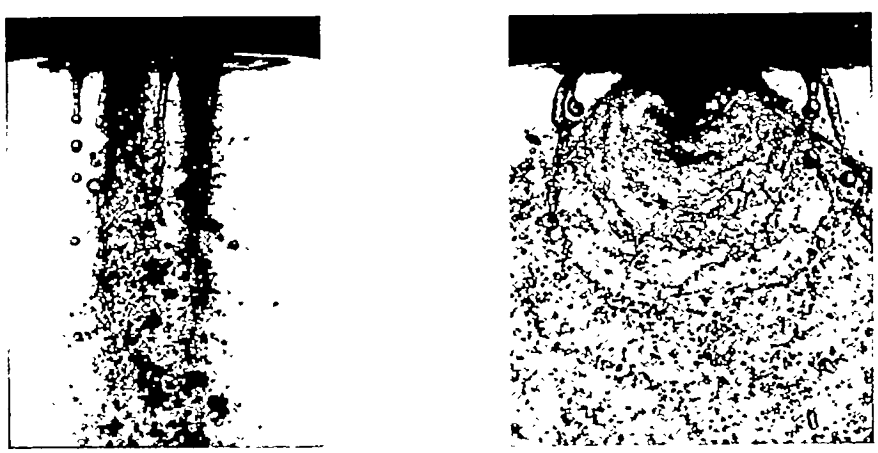


(d) Impinging-sheets injector; butt orientation of sprays.

Figure 1. - Continued. Injector design and water-spray photographs.





(e) Parallel-sheets injector; parallel orientation of sprays.

Figure 1. - Continued. Injector design and water-spray photographs.

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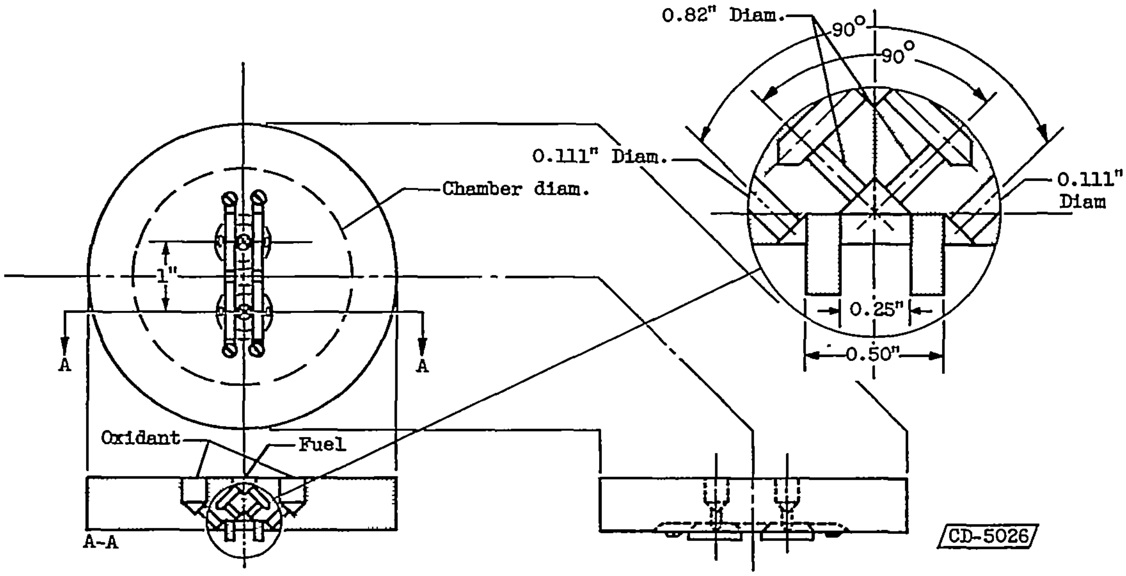
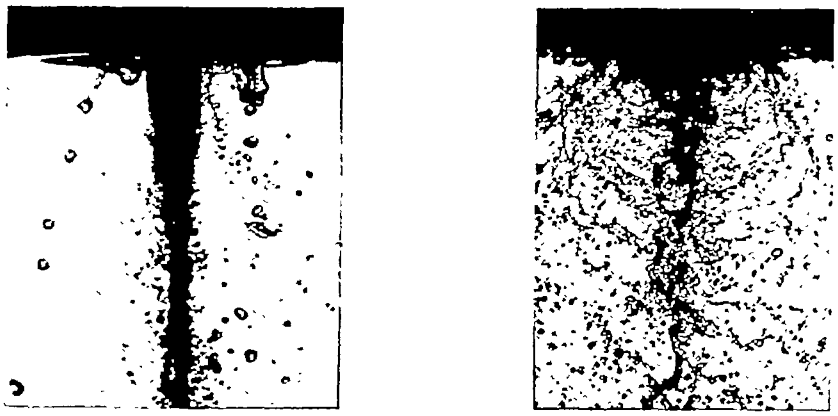
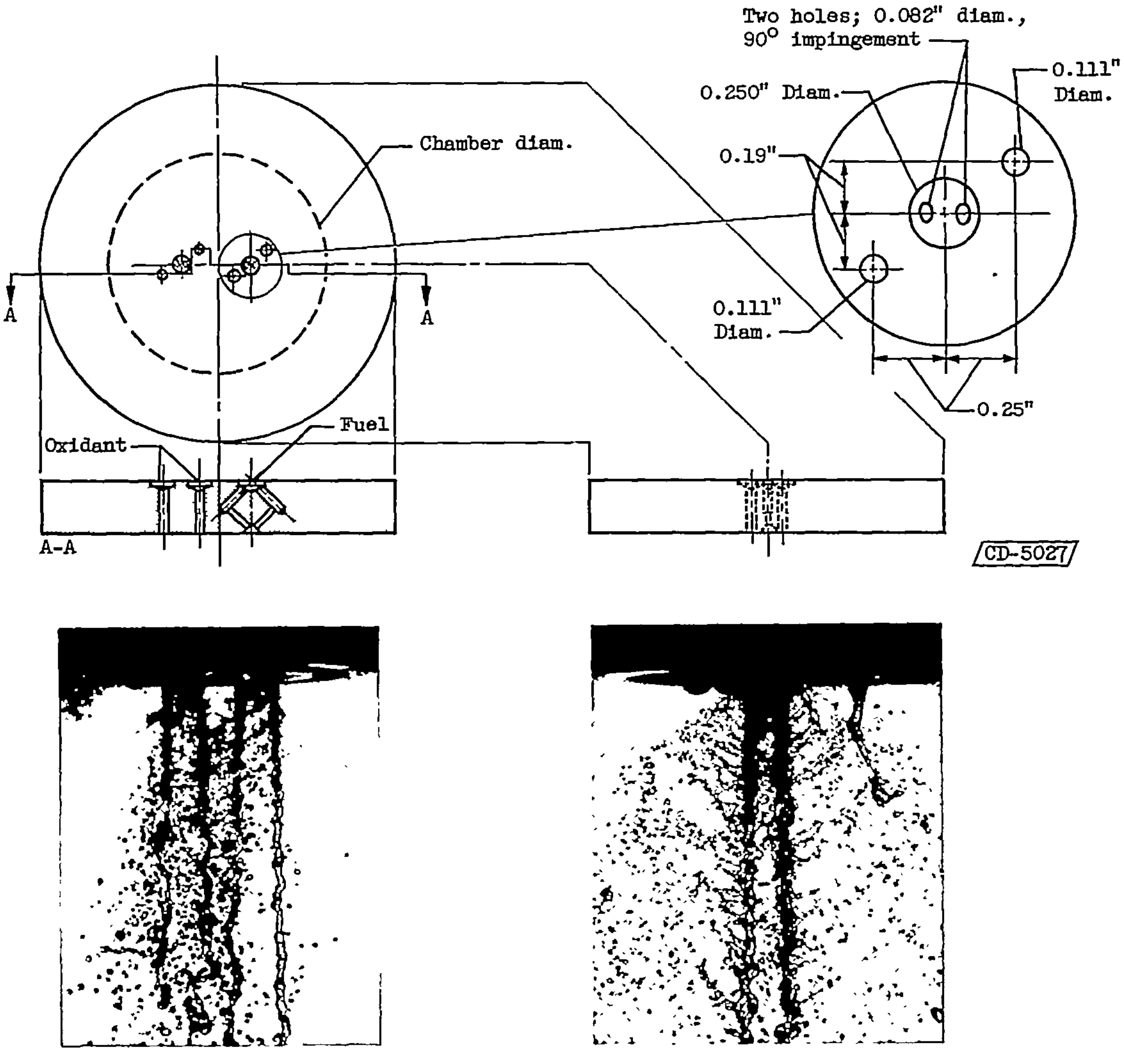




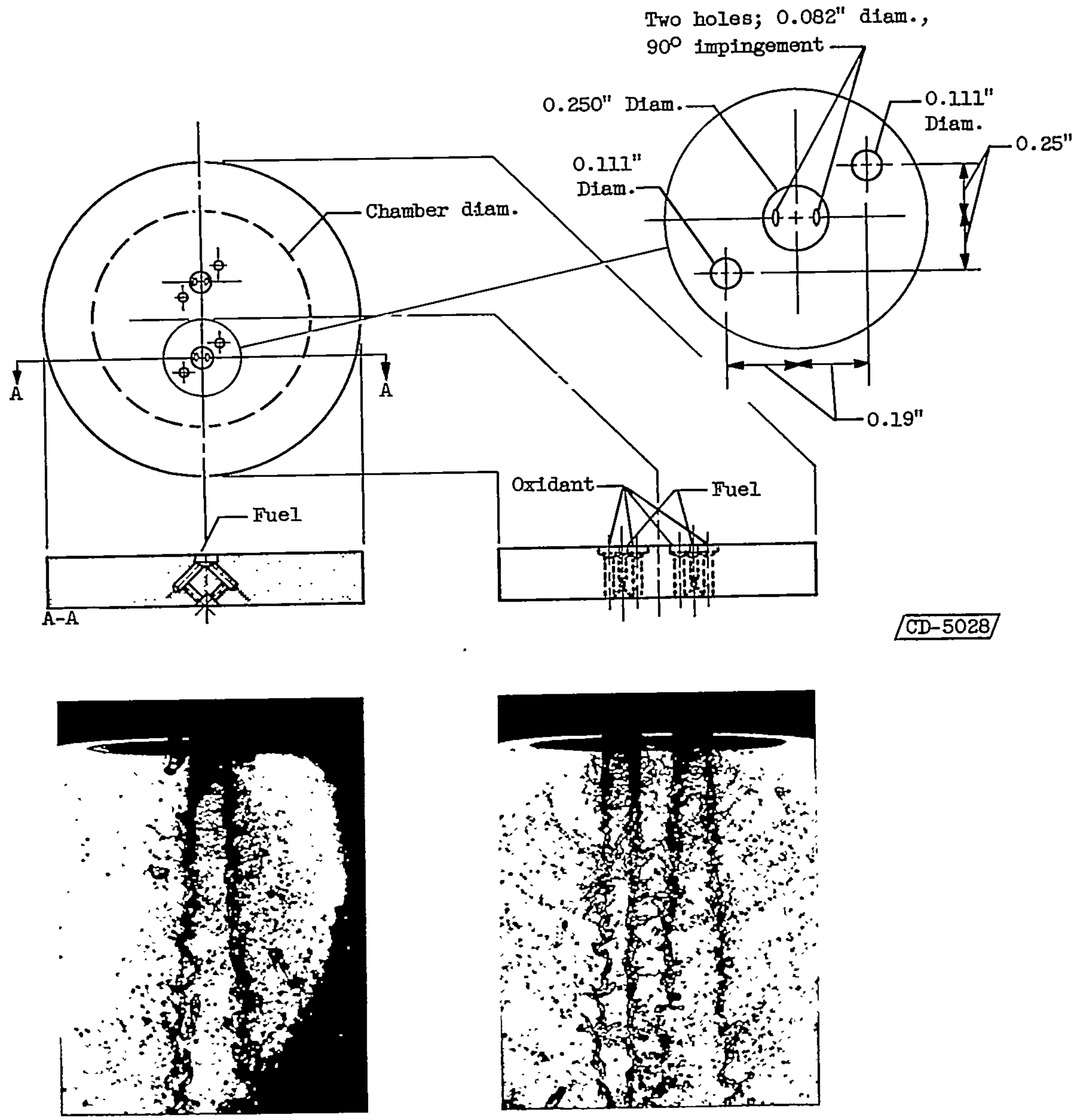
(f) Parallel-sheets injector; butt orientation of sprays.

Figure 1. - Continued. Injector design and water-spray photographs.



(g) Fuel-sheet - oxidant-jet injector; parallel orientation of sprays.

Figure 1. - Continued. Injector design and water-spray photographs.



(h) Fuel-sheet - oxidant-jet injector; butt orientation of sprays.

Figure 1. - Concluded. Injector design and water-spray photographs.

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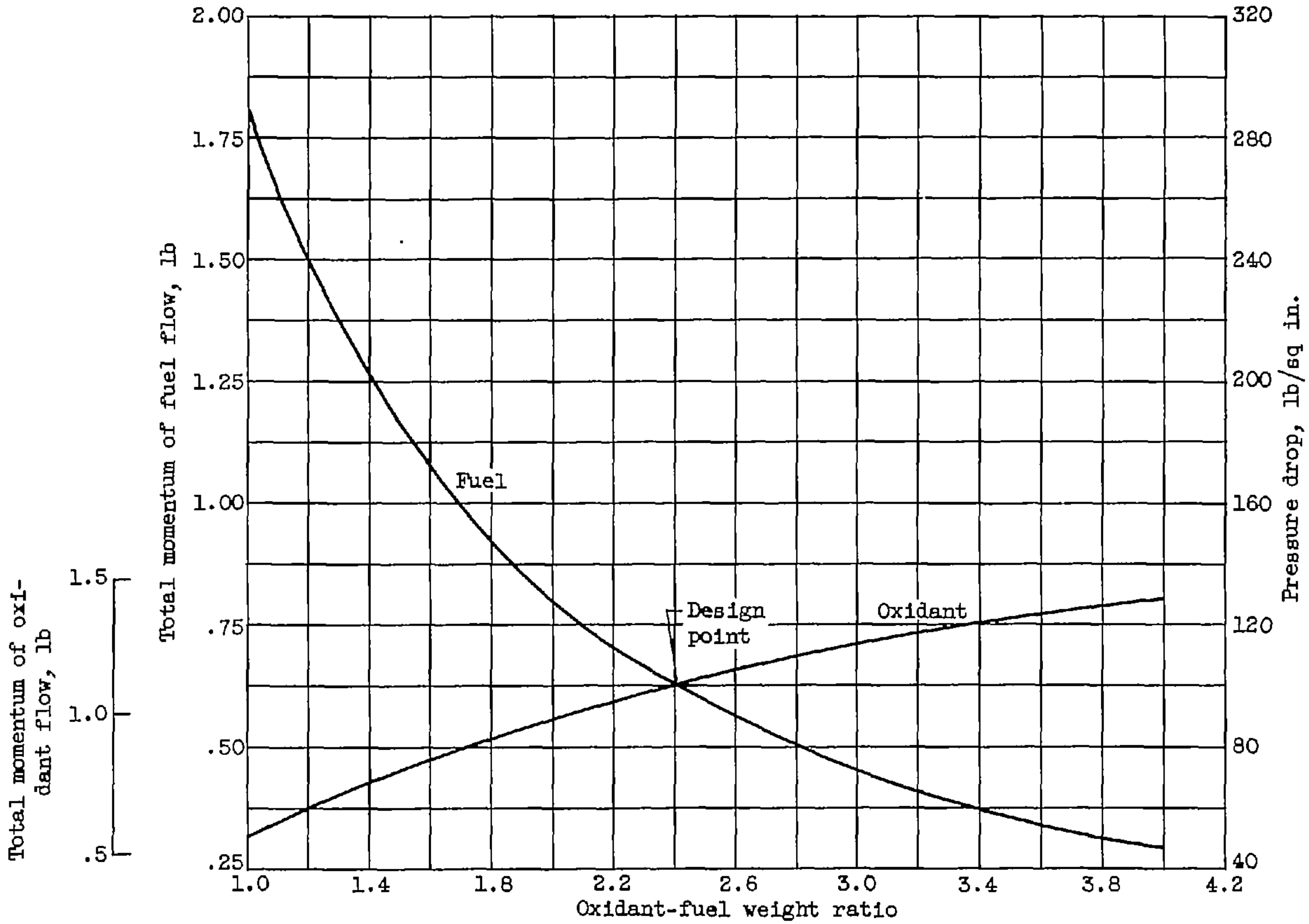

Figure 2. - Design pressure drop and total momentum characteristics for propellant flow from single element.

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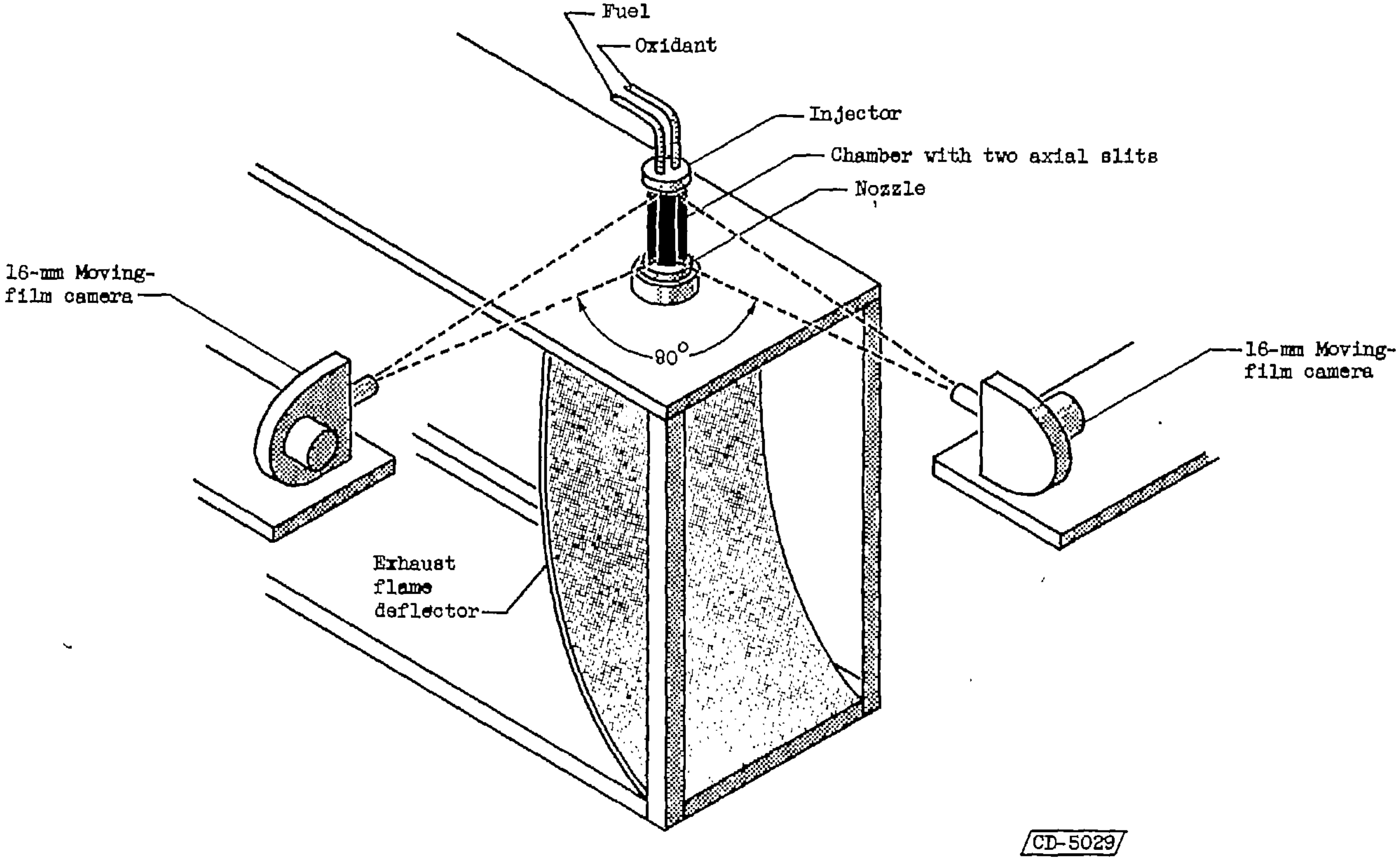

Figure 3. - Rocket engine and photographic arrangement.

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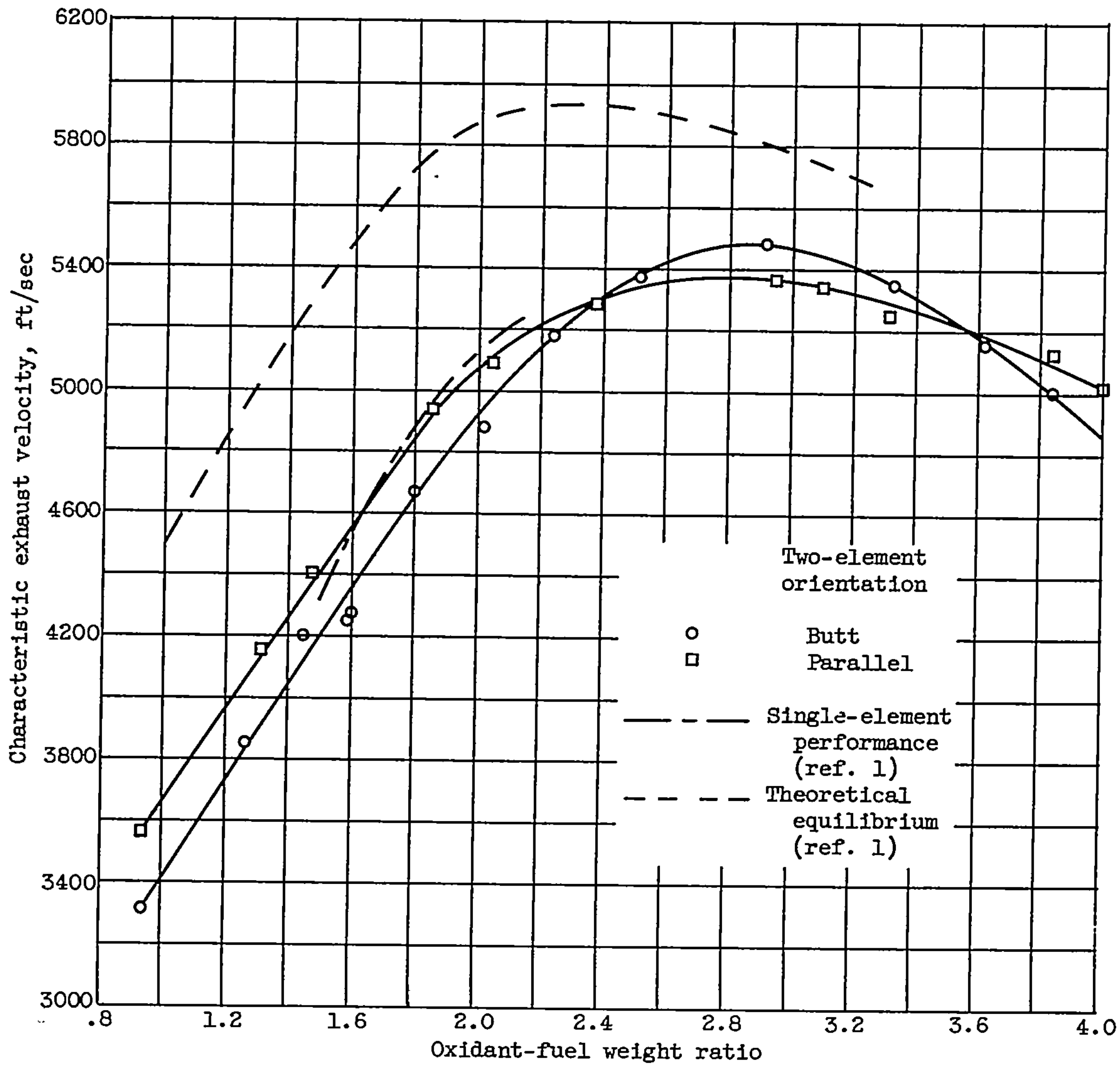

(a) Atomization after mixing (impinging-jets injector).

Figure 4. - Performance characteristics of several injection methods.

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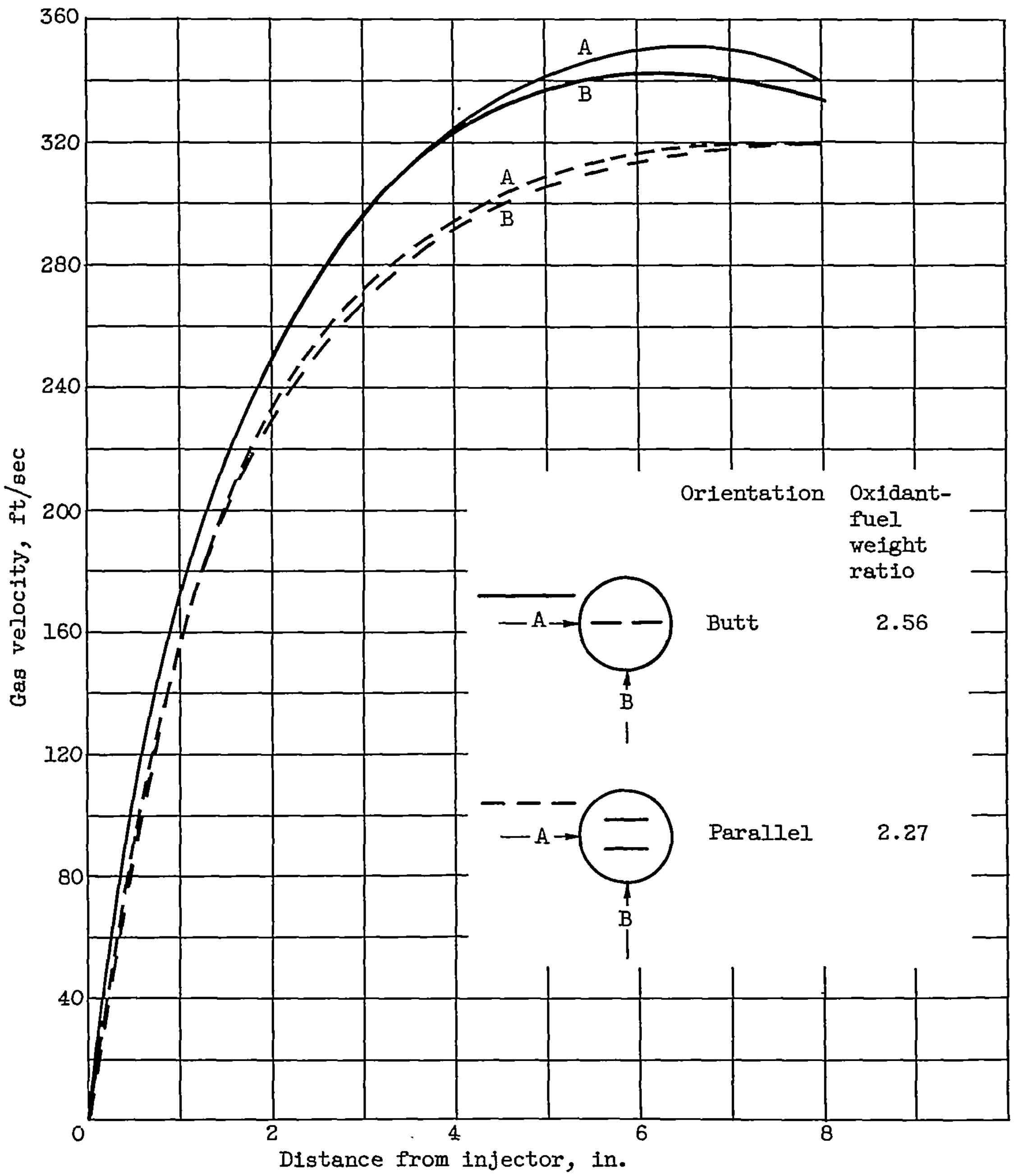

(a) Concluded. Atomization after mixing (impinging-jets injector).

Figure 4. - Continued. Performance characteristics of several injection methods.

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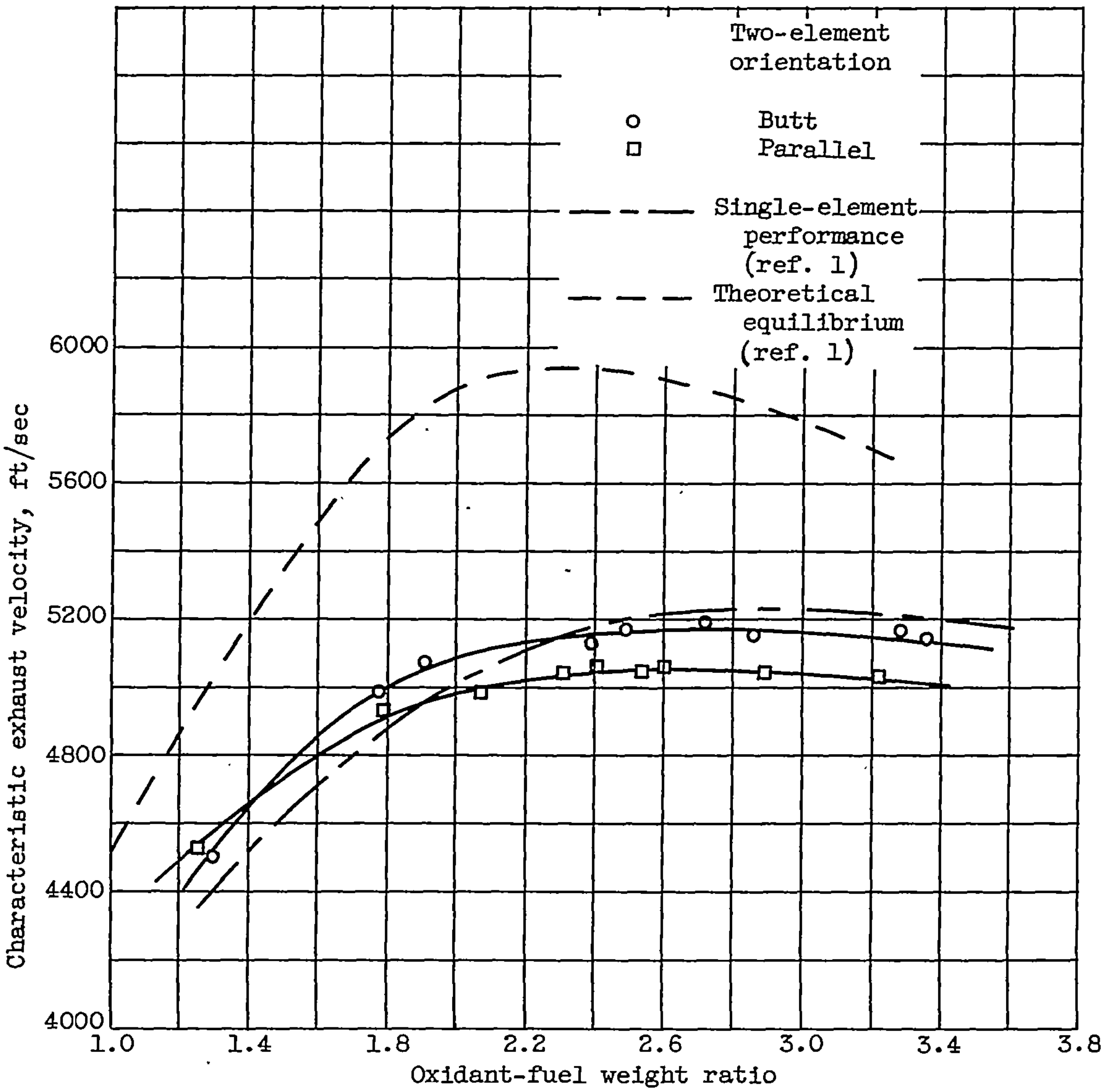

(b) Atomization before mixing (impinging-sheets injector).

Figure 4. - Continued. Performance characteristics of several injection methods.

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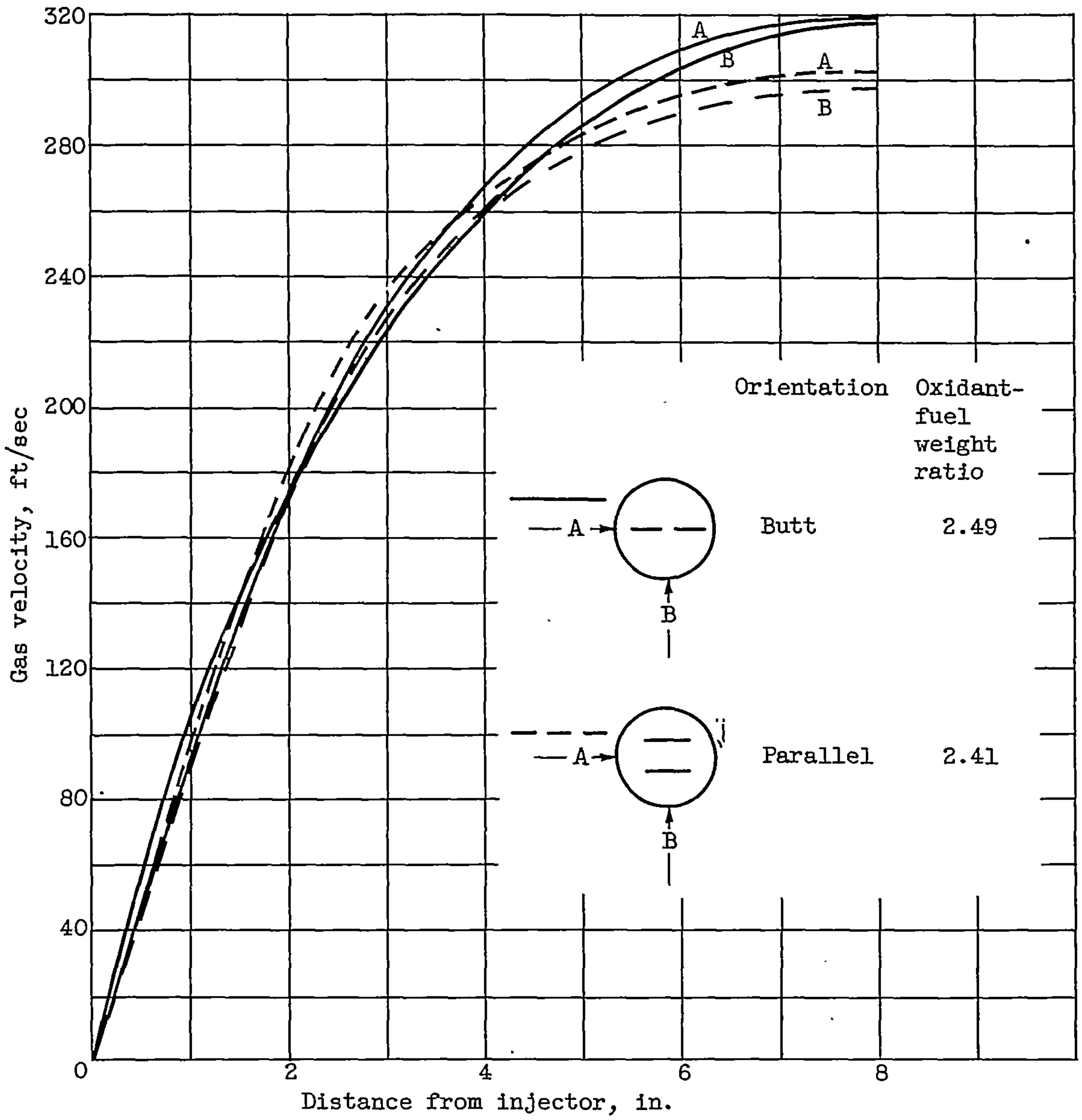
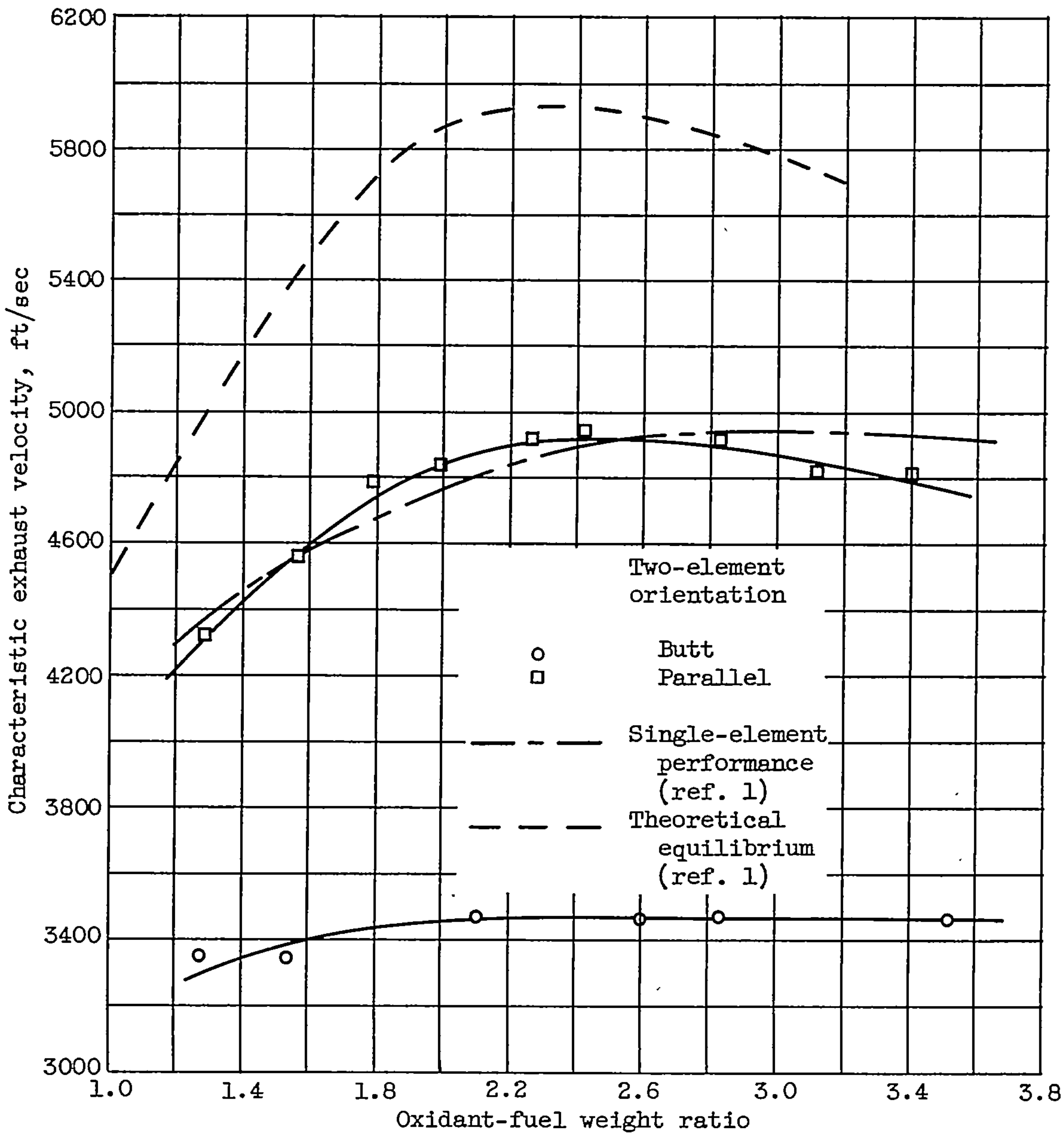


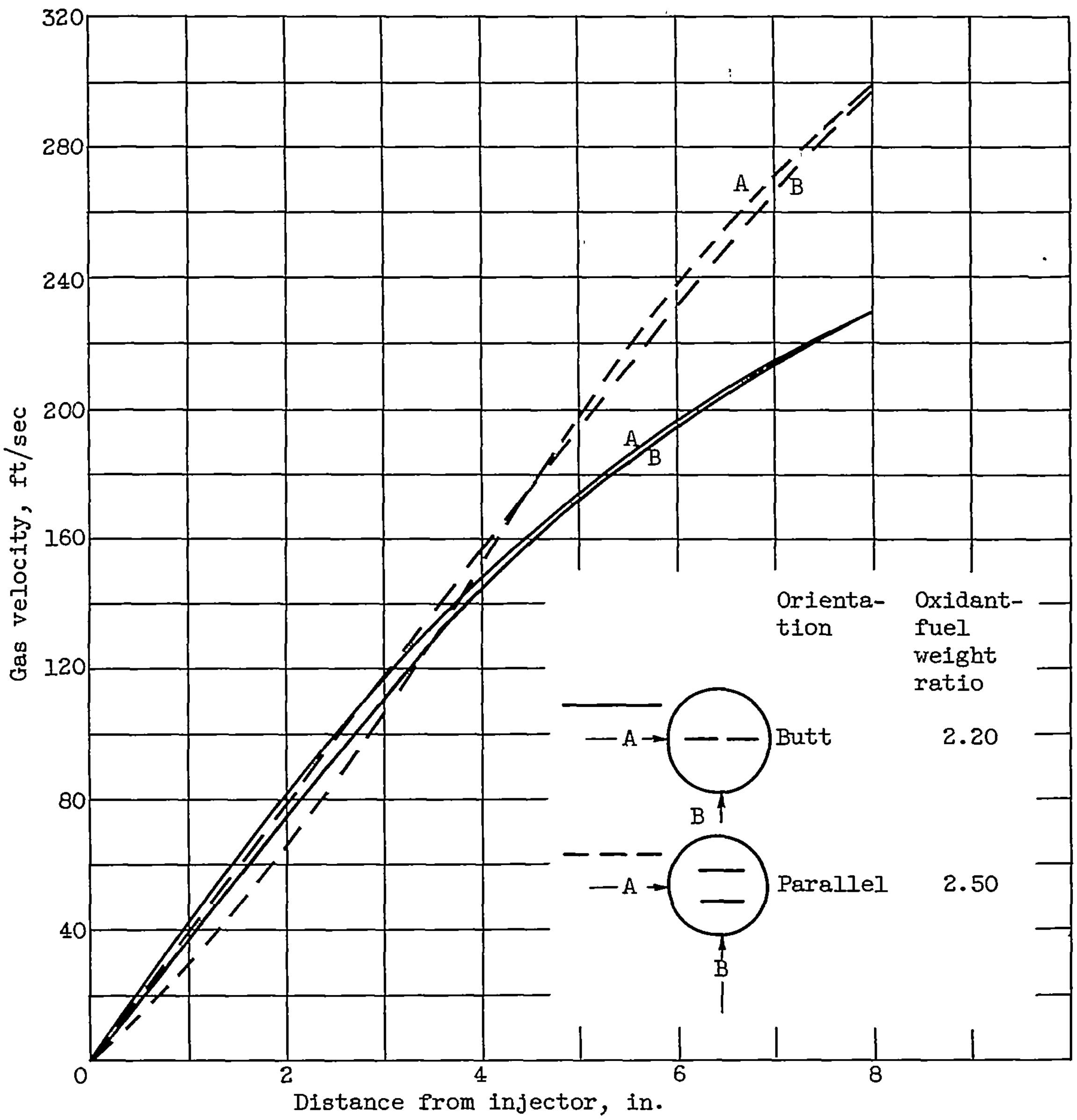
(b) Concluded. Atomization before mixing (impinging-sheets injector).

Figure 4. - Continued. Performance characteristics of several injection methods.



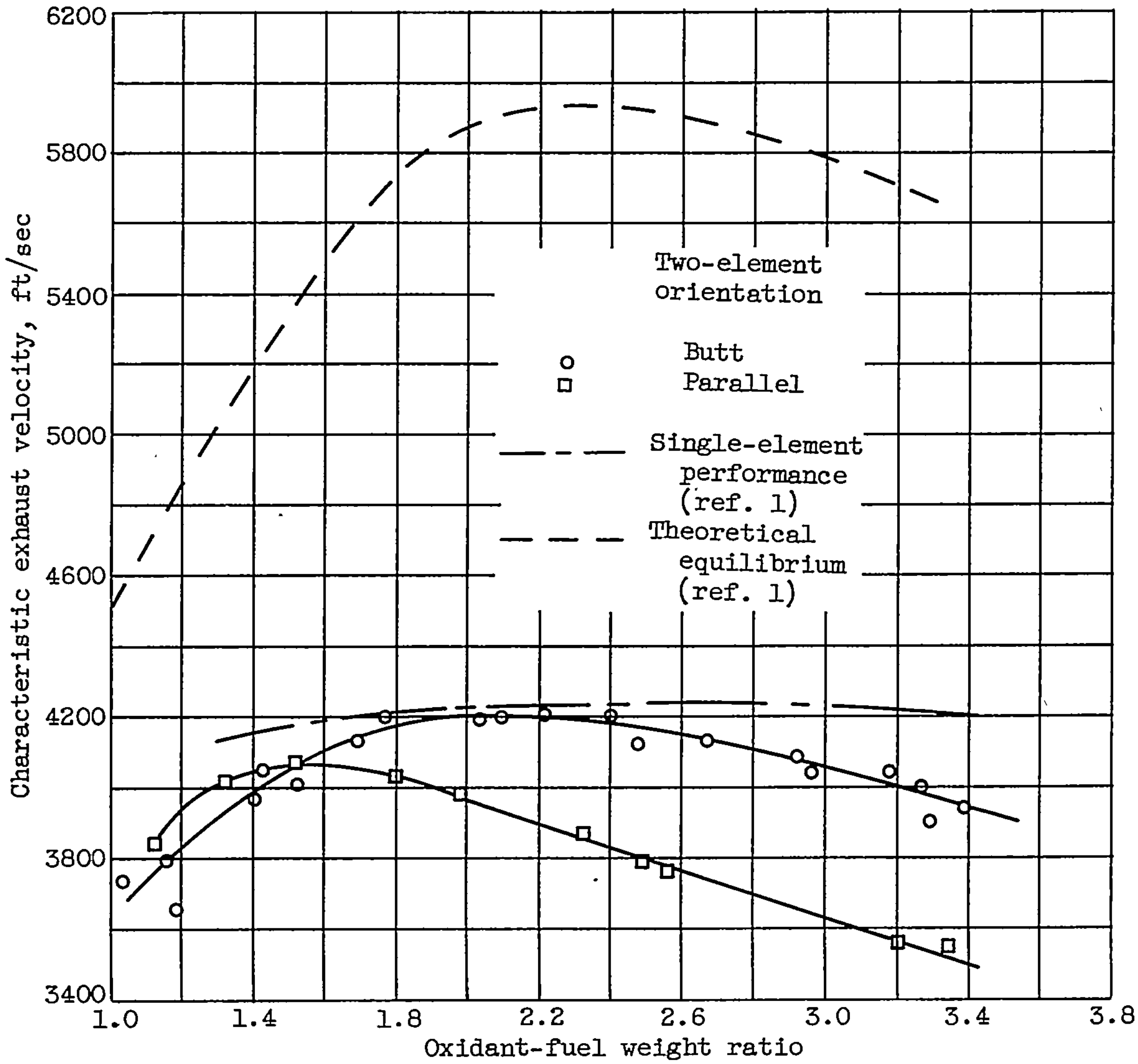
(c) Atomization without mixing (parallel-sheets injector).

Figure 4. - Continued. Performance characteristics of several injection methods.



(c) Concluded. Atomization without mixing (parallel-sheets injector).

Figure 4. - Continued. Performance characteristics of several injection methods.



(d) Fuel atomization without mixing (fuel-sheet - oxidant-jet injector).

Figure 4. - Continued. Performance characteristics of several injection methods.

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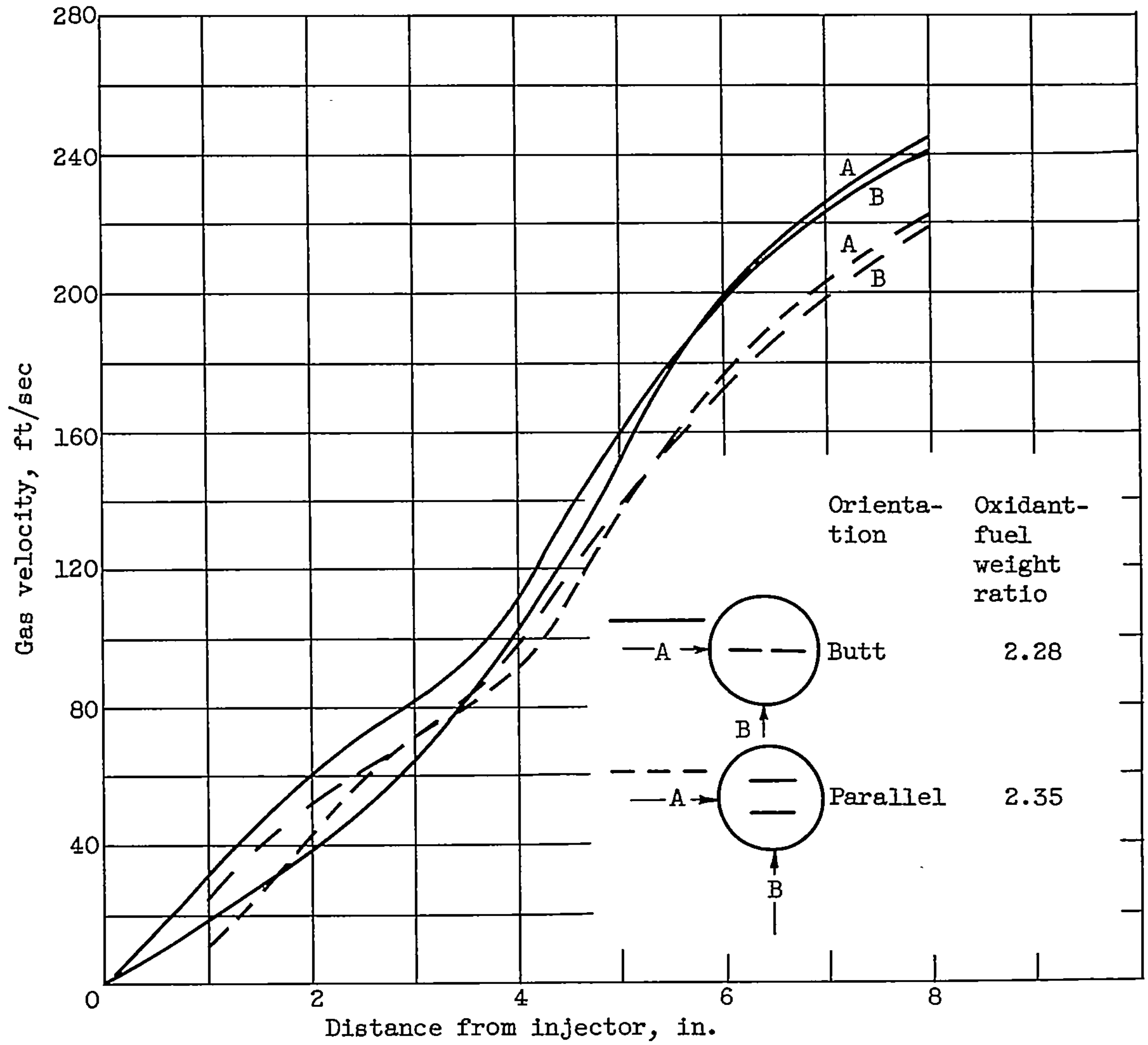

(d) Concluded. Fuel atomization without mixing (fuel-sheel - oxidant-jet injector).

Figure 4. - Concluded. Performance characteristics of several injection methods.

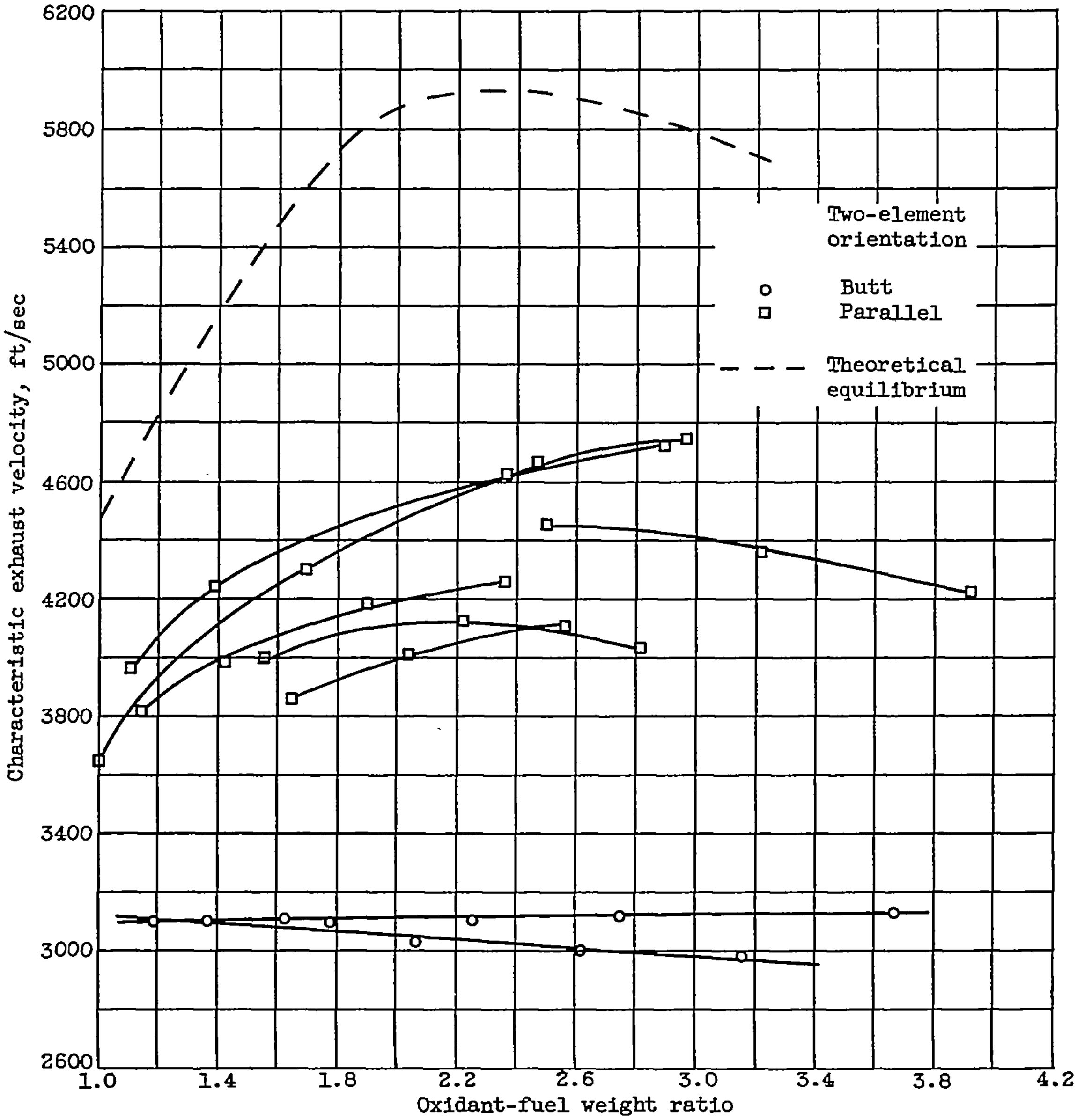

Figure 5. - Variation in characteristic velocity performance for atomization without mixing due to insert misalinement. Parallel-sheets injector.

NACA - Langley Field, Va.